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The U.S. Navy is addressing the primary causes of severe injury and death in survivable military helicopter mishaps through advancing crashworthiness technology. Computer simulation for both aircraft and occupant dynamics has been useful in defining the ideal crashworthy systems. Greater use of simulation is being employed to understand a wide range of crashworthiness-related areas. For example, the effects of a water impact on an aircraft structure are being evaluated, effects of occupant restraint system geometry are being analyzed, and the performance limitations on supplemental restraint systems can be determined. Advances in crash sensor technology has made it possible to integrate supplemental restraint systems into aircraft while adding a capability to record crash impact pulses. An increased awareness of occupant accommodation has brought about novel approaches for crashworthiness for an expanded anthropometric range for systems such as energy absorbers on crew and troop seats.

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EMERGING TECHNOLOGIES IN AIRCRAFT CRASHWORTHINESS

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ABSTRACT: The U.S. Navy is addressing the primary causes of severe injury and death in survivable military helicopter mishaps through advancing crashworthiness technology. Computer simulation for both aircraft and occupant dynamics has been useful in defining the ideal crashworthy systems. Greater use of simulation is being employed to understand a wide range of crashworthiness-related areas. For example, the effects of a water impact on an aircraft structure are being evaluated, effects of occupant restraint system geometry are being analyzed, and the performance limitations on supplemental restraint systems can be determined. Advances in crash sensor technology has made it possible to integrate supplemental restraint systems into aircraft while adding a capability to record crash impact pulses. An increased awareness of occupant accommodation has brought about novel approaches for crashworthiness for an expanded anthropometric range for systems such as energy absorbers on crew and troop seats.

INTRODUCTION:

Advances in crashworthiness technology achieved by the U.S. Navy are increasing the potential for aircraft to protect a larger anthropometric range of occupants in both ground and water mishaps. Many of these advances are attributable to computer design analysis, modeling and simulation, new materials, and increasingly capable dynamic testing facilities and methods.

The primary focus of aircraft crashworthiness is to protect occupants in a crash. To do this, the hazards that contribute to the injury mechanisms must be mitigated. During impact, there are two primary modes of occupant injury – acceleration-induced injury and contact injury. Reducing the acceleration-induced injury mechanisms requires absorbing impact energy through energy attenuation (i.e. crush zones, crashworthy landing gear, stroking seats). Reducing contact injury requires diminishing the occupant strike envelope through occupant restraints, cargo restraints, reduction of structural intrusion from the airframe into cockpit and cabin space, and making potential hazards more "strike-friendly" (i.e. rounding sharp edges or padding hard surfaces). This paper will examine recent developments in crash modeling for both the aircraft and the cockpit crashworthiness subsystems, as well as advances in occupant restraints and seat energy-absorbing characteristics.

AIRCRAFT-LEVEL CRASHWORTHINESS ANALYSIS:

Developers of next generation military and civil helicopters will have access to both new and substantially improved crash analysis methods that will enable more effective, efficient, and verifiable crashworthy aircraft designs. Many of the military helicopters being flown today were developed before dynamic crash analyses computer codes were available, and before required computational capabilities even existed. Aircraft such as the UH-1, H-3, and H-46 were developed based only on static load factors as structural crash criteria, with associated static stress analyses, and static load tests for crashworthiness verification.

Static crash load factors have typically ranged from 9g's to 20 g's in various axes for civil and military aircraft, and are intended to guide airframe designs to prevent intrusion of high mass items, and to structurally secure life critical items such as seating systems. Crash load factors represent static load equivalents of peak dynamic values for anticipated crash acceleration pulses. Since they are used as static loads, they

have the benefit of being relatively easy to apply from an analytical standpoint. However, when used alone as criteria, static load factors do not require designers to consider the influence of dynamically applied crash loads on airframe structures, nor do they require designers to consider the influence of crash induced airframe deformation at localized impact zones on structural capability.

For an airframe structure to provide more effective crash protection, it must be designed as a dynamic energy management system that provides predicable load attenuating crush in anticipated impact zones, while maintaining structural integrity and habitable space in occupied spaces. This approach, embodied in the Aircraft Crash Survival Design Guide [1], specifies survivable impact velocities that supplement static load factors, and further specifies volume reduction limits placed on occupied spaces. These dynamic crash requirements demand more advanced analytical methods to design and validate aircraft crash protection systems. To date, four U.S military helicopters have been designed based on these principles, consisting of the UH-60, AH-64, RAH-66, and V-22.

The hybrid KRASH code [2, 3, 4] has been widely used as a crash analysis tool for recent operational helicopters. The KRASH code permits aircraft designers to model an aircraft as a system of lumped masses, beam elements, and crush springs for dynamic crash analyses (Figure 1). KRASH is referred to as a hybrid model because, while it is a predictor of overall aircraft response to impact, it also requires that some aircraft crash response characteristics be supplied as input. For example, airframe crush characteristics at impact points are treated as crush springs and must be provided from test results, data bases, or estimates. Once a KRASH model is created it can be effectively used to predict global aircraft response to impacts, such as estimating accelerations of major masses and predicting failures of and between major structural regions. It is especially well suited for conducting preliminary design analyses of overall aircraft configuration options because KRASH models are relatively easy to create, and do not require complete structural design definition of the aircraft. KRASH is also useful when it's necessary to perform a large number of simulations (parametric analyses) at any stage in the development process since it can be run on a PC workstation. Upgrades to the commercially available KRASH code supplied by Dynamic Response Inc. have extended its capabilities to include water impact simulation at various sea states [5].

In future aircraft development efforts, dynamic non-linear finite element model (FEM) codes will likely be used in combination with the KRASH code as a complementary crash analysis approach. The value of dynamic non-linear FEM codes is that they permit detailed analyses of crashworthiness structures in dynamic environments without the need for empirical structural response data, such as load-deflection characteristics for crushable structures. Once the FEM is created, crash simulations can predict airframe crush characteristics, accelerations, and stresses throughout the structure. Detailed models of key localized structures can also be created and used to provide the necessary inputs for a KRASH model of the overall aircraft.

The U.S. Navy is currently exploring the use of two crash analysis codes as complementary tools for both land and water impact simulation [6], as shown in Figure 2. The effort, which is co-sponsored by the FAA, is being conducted through a Small Business Innovation Research (SBIR) effort that includes Dynamic Response Inc. as the prime contractor, with subcontractors consisting of Bell Helicopter Textron Inc. and

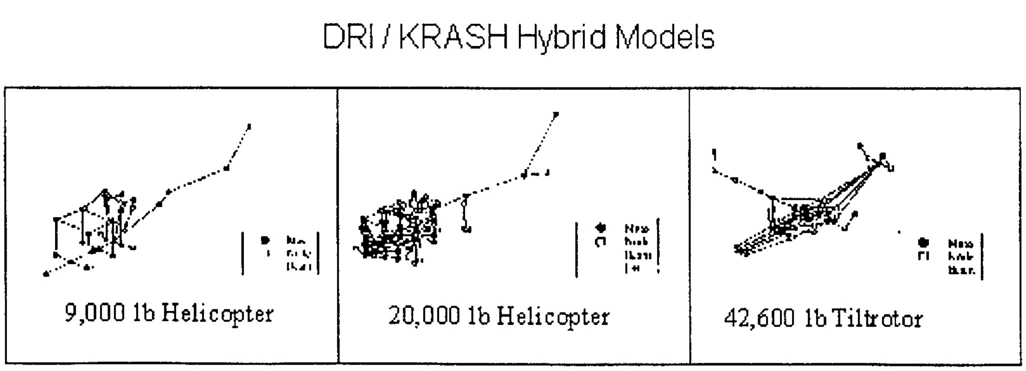


FIGURE 1: DRI/KRASH Hybrid Models

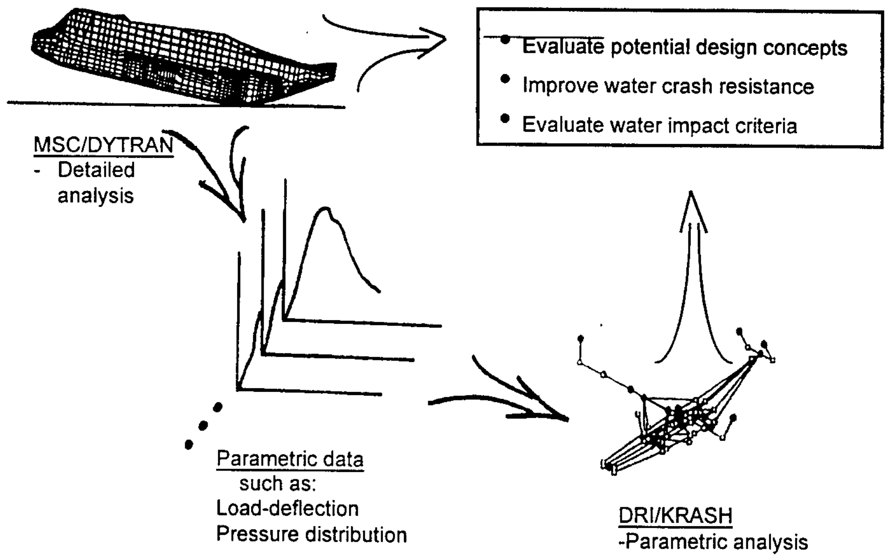


FIGURE 2: Combined Crash Analysis Approach Using DRI/KRASH and MSC/DYTRAN

Simula Technologies, Inc. In this effort KRASH models and MSC/DYTRAN models have been prepared of UH-1H and V-22 aircraft for use in water impact crash simulations. The MSC/DYTRAN model of the V-22 during a water impact simulation is shown in Figure 3. Results of the simulations are being compared to scale model ditching tests of the V-22, and full scale crash tests of UH-1H aircraft into water. The full-scale crash tests (Figure 4) are being performed under the SBIR by the Army Yuma Proving Ground. The test facility was jointly established by the Army Yuma Proving Ground and Simula Technologies, Inc. under a Cooperative Research and Development Agreement (CRADA) [7]. Objectives of the SBIR research are to demonstrate the capability of both codes for predicting water impact structural response, to provide water impact crash data to verify predictions, and to begin developing combined ground/water crashworthiness criteria and design concepts.

Initial results of the SBIR have verified for the first time that water impacts have significantly different crash characteristics than that of ground impacts, requiring different design approaches for crash protection. For example, crash pulse

MSC/DYTRAN Model

Eulerian fluid mesh
32,400 solid elements for water
10,800 solid elements for air

Lagrangian structural mesh
2,977 planar elements for aircraft

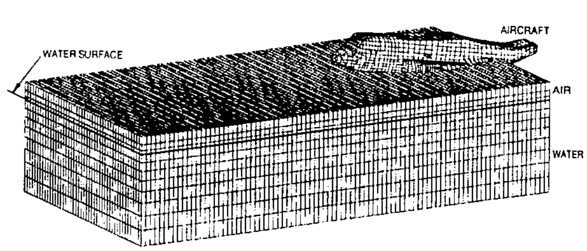


FIGURE 3: V-22 MSC/DYTRAN Model in Water Impact Simulation

acceleration onset rates for water impacts were found to be approximately 5 times higher than that of ground impacts. These high onset rates, caused by widely distributed and sudden hydrodynamic loading, require additional energy absorbing stroke from seats to safely attenuate forces transmitted to seat occupants. Airframes designed principally for ground impacts typically rely on sub-floor beams to crush and transfer attenuated crash loads to surrounding structure. However, in ground impacts, this design approach can fail when hydrodynamic forces are unable to load the beams after multiple skin panel ruptures. Perhaps the most obvious problem of water impacts is the inability for energy absorbing landing gear to contribute to the overall energy management system when contacting a fluid surface. For contemporary crashworthy aircraft, the landing gear is typically designed to absorb over 75 percent of the overall impact kinetic energy.

New energy absorbing approaches will be needed for joint service multi-purpose aircraft that are expected to include both ground and water impacts. One such approach has been suggested by the National Aerospace Laboratory in the Netherlands, and is referred to as a Tensor-skin Concept [8]. In this approach, the skin panels unfold to provide a bowed surface under hydrodynamic loading. The bowed skin panels transfer sufficient vertical loading to initiate energy absorbing crush in adjacent beams, without experiencing rupture. Designs such as this could also enhance crash response in soft soil.

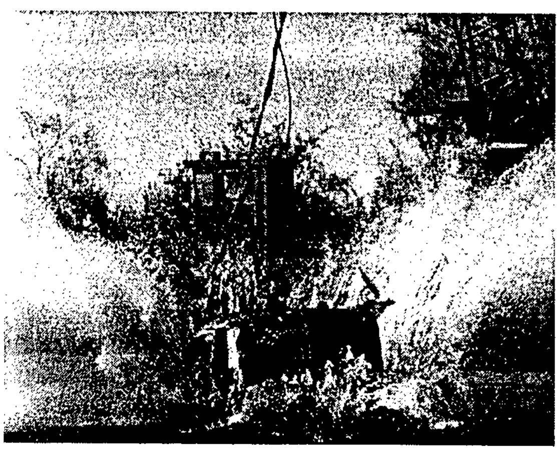


FIGURE 4: Water Crash Test of a UH-1H Helicopter

Extensive structural crash analysis research is also being jointly performed by the Army Research Laboratory and the NASA Langley Research Center. In this effort [9] MSC/DYTRAN is being utilized to model an all composite helicopter and simulate rigid surface impact conditions. The overall objective is to establish and validate aircraft crash modeling methodologies for development of future aircraft, with a focus on ground impacts. A full-scale crash test was recently conducted of the all-composite helicopter using the NASA Impact Dynamics Facility. This data is currently being analyzed to correlate simulation predictions.

SUBSYSTEM-LEVEL CRASHWORTHINESS ANALYSIS:

Airframe-level crashworthiness concerns are important for mitigating the energy of a crash. However, crashworthy subsystems such as restraints and seating are important for keeping occupants from being thrown about the cockpit or cabin (or out of the aircraft altogether), encountering strike hazards, attenuating the energy directly applied to the occupant, and keeping occupants' bodies in a posture that can best withstand crash forces and accelerations.

Advances in the crashworthy subsystems of automobiles have been driven by government regulations for improved occupant restraints such as airbags. With designers focusing more on occupant safety, analytical tools for impact simulation have been developed that are also useful for aircraft crash scenarios and occupant response.

IMPROVED RESTRAINT SYSTEMS:

Inflatable Restraints:

Belt-Mounted Systems: Throughout the 1980's and 1990's the U.S. Navy and Army developed the Inflatable Body and Head Restraint System (IBAHRS). This shoulder harness-mounted inflatable system was activated by a crash sensor and had the purpose of removing slack in the shoulder harnesses on a 5-point restraint system (Figure 5). Recent regulations by the Federal Aviation Administration to increase safety for commercial airline passengers seated directly behind bulkheads has also spawned new innovations in the area of belt-mounted inflatable restraint systems.

FIGURE 5: Inflatable Body and Head Restraint System

While IBAHRS consists of inflatable bladders which would inflate between the shoulder harness webbing and the occupant's chest, some new concepts for belt-mounted inflatable restraints have webbing-mounted airbags which inflate outward to full-size to protect the occupant's head and chest from striking a bulkhead, another seat, or even to keep the head from striking the occupant's knees.

However, the concept of using a webbing-mounted inflatable restraint to remove slack in the restraint system has reached a new generation. Now designed and marketed to the automotive community, inflatable restraints are being mounted on the shoulder-portion of three-point seat belts. Simula Technologies, Inc., who developed the original IBAHRS, has integrated an airbag structure into the seat belt which shortens as it inflates, thus removing slack.

Aircraft Airbag Systems: Airbag technology, widely introduced in automobiles during the 1980's, is now being adapted for helicopter cockpits. The U.S. Army began development of a Cockpit Airbag System (CABS) for its helicopter platforms in the early 1990's. The concept for attack helicopter platforms with tandem seating such as in the AH-1 Cobra and the AH-64 Apache has three airbags per crewstation – a forward bag to protect from strike hazards such as the cyclic stick and the telescopic sighting unit, and two lateral airbags to protect the pilot and gunner from head strikes against the seat armor panels (Figure 6).

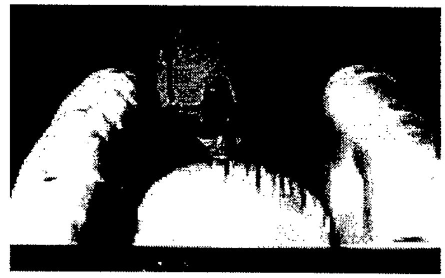


FIGURE 6: Cockpit Airbag System Concept for Attack Helicopters

Advanced development on the CABS program expanded to become a joint service effort under Army lead, including the Navy, Air Force, Coast Guard, and FAA. The project then concentrated on platforms with side-by-side pilot/copilot seating and chose the H-60 as a joint service platform for CABS development. The system currently in Engineering/Manufacturing/ Development program for the Army UH-60 platform has provisions for four airbags per cockpit (Figure 7). The frontal airbags are designed to protect against head and chest strikes on the cyclic stick or instrument panel. Lateral airbags, mounted on the seat armor panel, are designed to protect against strikes on that hard surface and offer some protection from intruding structure.

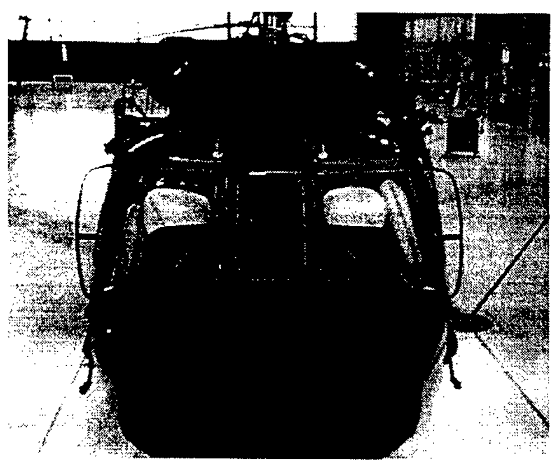
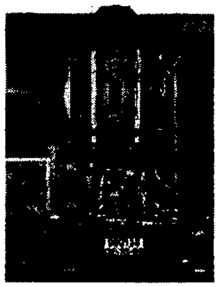


FIGURE 7: Cockpit Airbag System Static Inflation in the UH-60



(a)

(b)

FIGURE 8: Advanced Energy Absorber (a) Pre- and (b) Post-Test on a UH-60 Blackhawk Seat

While an advanced EA would be relatively easy to retrofit into airframes which already have crashworthy seating, a different problem occurs in trying to retrofit crashworthy capability into airframes without stroking seats. One possible solution is to design a seat cushion that can provide energy attenuation when simply replacing a non-crashworthy cushion. A Navy Small Business Innovation Research Program is currently examining doing this for airframes such as the AH-1W, which have limited crashworthy capability. The prototype design by Triangle Research and Development Corporation for this program employs an air channeling system in a 10 cm thick cushion which will be undergoing preliminary testing in the near future.

One interesting application of the seat stroke is in a patented concept by Sikorsky Aircraft Corporation, which is developing the idea of using the downward motion of the stroking seat to direct the motion of a crashworthy cyclic stick away from the strike zone of the seat occupant through the use of cables, pins, and ratchets.

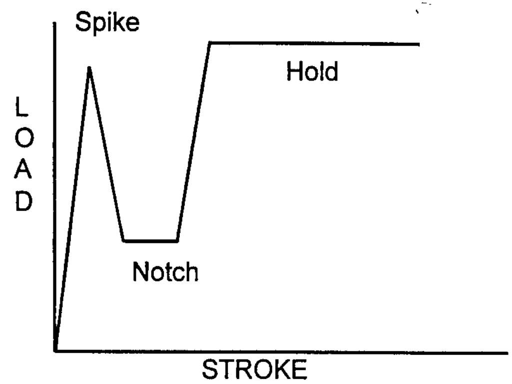
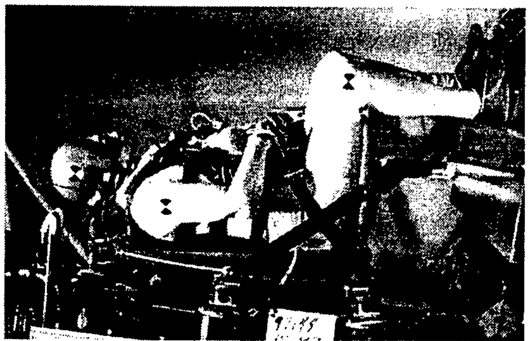


FIGURE 9: Advanced Energy Absorber Notched Load-Stroke Profile

Troop Seating: Developing effective crashworthy troop seating for military aircraft has additional challenges over troop seat development. Because there are several troop seats per airframe, the weight of an individual seat must be kept to a minimum. The seats must be easily removable, protect a range of occupant weight that will include both a small woman and a large man with a heavy backpack, and be effective in forward-, aft-, and side-facing seat orientations. Also, the effects of the seat loads on the airframe must also be considered so that seats remain attached to the aircraft during an impact (Figure 10) [11].

New technologies to improve crashworthy seating will most likely focus on EA design that is both lightweight and accommodates the expanding occupant range. Solutions such as EA's with variable-thickness wire-benders, multiple-stage wire-bending mechanisms, and energy-absorbing foams have been developed. Another focus will be on restraint-system integration that is designed for a side-facing seat that may encounter several different impact orientations.

The Navy has developed advanced troop seats through East/West Industries, Ronkonkoma, New York, in the Airborne Adaptively Attenuating Troop Seat Program. These seats safely attenuate vertical crash loads for the 5th percentile female through the 95th percentile male anthropometric range and structurally react 23 g longitudinal loads.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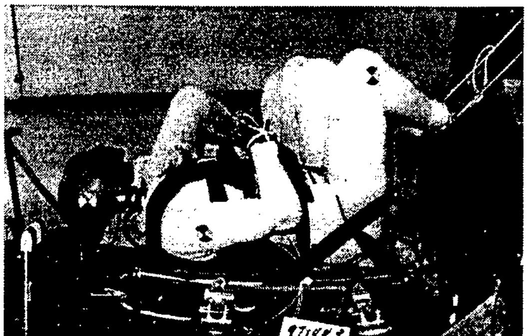
(b)

FIGURE 10: Crashworthy Troop Seat Dynamic Testing (a) Pre- and (b) Post-Test on a H-53 Troop Seat, Gyz Test Orientation

MODELING AND SIMULATION:
Modeling and simulation tools developed for the automotive industry are finding increasing use in the aircraft crashworthiness area as well. The usage of lumped-parameter simulation packages such as ATB and DYNAMAN is becoming increasingly sophisticated. On the other end of the spectrum, automotive applications using completely finite element models of vehicles and occupants are increasing as well. The middle ground between these two modeling methods would be a hybrid software package such as MADYMO (Figure 11), which primarily uses lumped-parameter models but integrates some finite element features for seat belts and airbags.

While computer simulation could never replace actual hardware dynamic testing, it is useful in design applications for determining "ideal" restraint geometry for several sizes of occupants, reducing weight, and determining the limits of ideal system performance.

The new frontier in occupant safety modeling and simulation is the development of occupant models based not on anthropometric test devices (ATD's) such as the Hybrid III test dummy, but based instead on human anatomy. Much work has been done to adequately model the human neck and spine, lower extremities and head. The benefits of these types of models are that they may indicate potential injury to human bones, muscles, and organs that could not be indicated with the use of an ATD.

FIGURE 11: MADYMO Model of a Side-Facing Troop Seat

CONCLUSIONS:

New concepts and technologies being explored and developed through the U.S. Navy are advancing the life saving capability of crash protection systems. These advancements are directed towards providing cost-effective crash protection across diverse Navy missions, aircraft, and associated crash environments. In future aircraft development efforts, new aircraft crash modeling methodologies will be used during the design and verification process to insure that aircraft have substantial crashworthiness capabilities for both land and water impacts. Crashworthy seating systems will employ new technologies such as advanced energy absorbers to provide greater impact protection for an expanded anthropometric range of pilots and troops. Improved restraint systems will also be available to protect occupants from strike hazards in pilot, crew, and troop stations. Together, these and other improvements will work to preserve the Navy's greatest assets; our highly trained pilots, aircrew and troops.

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